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13. ABSTRACT

Structural studies have yielded important results in two general areas: ~~we have determined~~ a high resolution mean earth model has been determined through the inversion of a very large quantity of free oscillation, surface wave and body wave data. This model gives especially detailed information concerning the lower mantle and the core of the earth; and secondly, through a variety of new techniques, ~~we have determined~~ details of the structure of the transition zones in the upper mantle and their lateral variability and similar results for crust and upper mantle structure, especially within the continental United States has been determined.

A complete treatment of stress relaxation due to an explosive shatter zone within a stressed medium was completed and appears to agree well with the observations. Predictions of radiation fields from sources of general type (relaxation, dislocation, explosive) in layered media were made and comparisons with observations begun. A number of separate studies based on the interpretations of radiated fields from earthquakes and explosions were undertaken and source parameters determined which provide a fit to the (limited) observational data. The resolution of source differences between earthquakes and explosions was significantly improved and uncertainties in the characteristics of earthquake and explosion spectra have narrowed, the principal verified result being that earthquake spectra are shifted to long periods relative to a comparable explosion, due to a larger characteristic dimension (the fault length) and generally lower rupture (or formation)rates.

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Table of Contents

Abstract

Structural studies have yielded important results in two general areas: we have determined a high resolution mean earth model through the inversion of a very large quantity of free oscillation, surface wave and body wave data. This model gives especially detailed information concerning the lower mantle and the core of the earth; and secondly, through a variety of new techniques, we have determined details of the structure of the transition zones in the upper mantle and their lateral variability and similar results for crust and upper mantle structure, especially within the continental United States. These results are in part a consequence of the development and application of asymptotic wave theories (in both the frequency and time-domain appproaches) during this research period and in part due to the use of older techniques, such as multiple reflections and spectral ratios, in new ways.

The refinement of powerful inversion techniques has been important in structural studies, and preliminary work in source studies has shown that source properties may be systematically investigated in a similar way.

Theoretical source studies have yielded concise representations of relaxation source models in terms of a Green's function formulation which allows for the consideration of general rupture geometries and stress conditions of the material within the fault zone. A complete treatment of stress relaxation due to an explosive shatter zone within a stressed medium was completed and appears to agree well with the observations. Predictions of radiation fields from sources of general type (relaxation, dislocation, explosive) in layered media were made and comparisons with observations begun. A number of separate studies based on the interpretations of radiated fields from earthquakes and explosions were undertaken and source parameters determined which provide a fit to the (limited) observational data. The resolution of source differences between earthquakes and explosions was significantly improved and uncertainties in the characteristics of earthquake and explosion spectra have narrowed, the principal verified result being that earthquake spectra are shifted to long periods relative to a comparable explosion, due to a larger characteristic dimension (the fault length) and generally lower rupture (or formation) rates.

I. Introduction

The present report summarizes work accomplished for the period 1 November 1970 to 31 October 1971. The research accomplished under this grant has been described in detail in the series of technical papers listed in section VII of this report. Abstracts of these publications and of papers presented at scientific meetings during this report period are given in section VI. The research has been divided into the following specific areas for the purposes of this report:

(1) Earth Structure and Inversion Theory
(2) Seismic Wave Propagation Theory
(3) Seismic Source Theory and Observational Studies
(4) Instrument Installation/Data Acquisition Systems

In sections II through V we briefly summarize the accomplishments and work initiated in these research areas during the past year.

II. Earth Structure and Inversion Theory

Our direct effort in this area involves two basic activities; the determination of seismic velocities, density, and anelastic properties for the earth from observational data derived from surface waves, body waves, free oscillations, and a variety of other geophysical data, and secondly the development of methods for the inversion of the observational data in a systematic manner so as to yield information concerning the intrinsic elastic-anelastic properties of the earth.

In addition to the intrinsic interest of the resulting earth models in studies of planetary formation and evolution, this work is immediately relevant for applications involving seismic discrimination, in particular for:

(1) Prediction of the seismic radiation fields from earthquakes and underground explosions

(2) Location and depth determination of events

(3) Understanding of basic tectonics and the nature of natural events

(4) Reduction of observed earthquake and explosion seismic field data, such as observed wave spectra, to determine source characteristics.

Further, our development of inversion methods, designed to yield earth structure, has much wider application, in particular to the inversion of seismic data for source properties. This particular application of the theory for inverse problems was begun during the past year.

We may conveniently summarize some of our accomplishments by noting some of the new techniques which were developed and applied in this area, in particular:

(1) The generation of synthetic, time-domain, seismograms using Cagniard's method for systematic comparison with observations to determine source properties as well as details of earth structure.

(2) Use of body wave spectral ratios from distant events in order to obtain crustal and upper mantle transfer functions, which in turn yield local crust-mantle structure at the point of observation when inverted. This approach can then be used to systematically investigate lateral variations in crust and mantle properties.

(3) Use of multiple reflections in order to determine the local depth of lower and upper mantle discontinuities; and then map the lateral variations of these discontinuities using a large number of events, widely spaced geographically.

(4) The generation of powerful and flexible inversion methods and programs capable of inverting any type of data, such as heat flow (thermal) data, seismic source data, or seismic data dependent on earth properties, to provide realistic estimates of the intrinsic properties of the system (e.g., the earth) to which the observed data are related. For example, for the earth's structure, we may use body wave travel times for a wide variety of direct or reflected phases, body or surface wave phase velocities, free oscillation spectra, mass and moment of inertia and equations of state to yield structural estimates with existing programs. Other programs, utilizing the same basic inversion theory embodied in a sub-program, can be used to invert heat flow, gravity, and seismic data together to obtain thermal properties of the earth; which is important in delineating structural provinces and tectonic regions.

(5) Application of refined asymptotic wave theory for the interpretation of seismic data (e.g., refractions and reflections) in terms of structural characteristics of the medium, for example, in terms of velocity gradients and/or anelastic properties.

(6) Development and application of the theory for the prediction of frequency shifts in free oscillation spectra (or phase shifts of surface waves) due to anelastic effects and determinations of anelastic properties from observations of the earth's free oscillation spectra.

While a complete summary of results obtained during the past year is provided by the abstracts in section III (see part A for earth structure and inversion studies), it is useful to survey, in a general way, the essence of what has been learned about the earth. In particular, our results provide:

(1) Resolution of details of the lateral variations between and within crust-upper mantle "structural provinces" for the continental United States using a variety of methods.

(2) High resolution mean earth models with especially useful and reliable information on the lower mantle and core structure.

(3) Determinations of fine structural details of the earth's upper mantle, in particular details of the lateral variability of upper mantle discontinuities and the nature of the radial velocity variation associated with these "discontinuities".

(4) Measurements of the earth's anelastic properties using both the amplitudes and periods of the earth's free oscillations (or alternatively the amplitudes and group or phase velocities of surface waves)--with results indicating the bounds for the possible frequency dependence of the intrinsic Q factor for the medium as well as its depth variation.

These results have a direct impact on studies directed to discrimination of seismic events as we mentioned earlier. The applications of our structural study results in this area were directed toward: (1) the prediction of seismic source fields with comparisons to observations using a variety of theoretical source models, and (2) the reduction of observational data, amounting to a removal of the effects of wave propagation through the earth, in order to determine source properties, particularly the equivalent source spectrum. Considerable effort was directed along these two lines of investigation, and it is clear that success in this area is dependent on structural studies of the kind we have pursued. These source studies are summarized in section IV, along with the theoretical studies of seismic sources.

III. Seismic Wave Propagation Theory

Our work in seismic wave propagation theory provides the basis for the interpretations of the observational data leading to determinations of structure and the seismic source itself. It has therefore been closely allied to the more applied problems involving structure and source studies. Thus during the past year, we have emphasized research in one of the more underdeveloped theoretical areas, asymptotic wave theory, since we believe that the largest return in the areas of immediate interest result from applications of this theory. Examples of the usefulness of the theory developed have already been mentioned in the previous section, where estimates of velocity gradients and the earth's anelastic properties have been obtained, in addition to an understanding of the amplitude behavior of both reflected and refracted seismic phases. Applications to observational studies of seismic sources are discussed in the following section.

One approach to asymptotic wave theory provides results in the time domain so that comparisons can be made directly with seismograms. This has some intrinsic advantages over frequency-domain representations since the more subtle phase information, as well as amplitude information, is integrated into our interpretations. This approach uses the well-known Cagniard method. One aspect of this work involves wave propagation in the crust at large distances, 400 to 1200 km, which has not been thoroughly studied from this point of view. We are looking into this problem both theoretically and observationally. Observations from both earthquakes and large NTS events, including short- and long-period LRSM recordings, have been analyzed and the results used in both structural studies and in source studies. These results are summarized in sections II and IV. Much of the

theoretical work using the time-domain approach has been incorporated in studies of the earth's structure and in seismic source studies, and hence is reported in the abstracts listed in these two areas.

We have strongly emphasized the theoretical development of a practical, higher-order ray theory, and hence have developed the asymptotic wave theory in the frequency domain. This work is specifically designed to yield an accurate theory to be used to interpret amplitude spectra data obtained from waves refracted, reflected, or with turning points at and near zones of rapid velocity variations, such as the crust-mantle boundary and the various upper mantle transition zones. It is for such waves that simple ray theory predictions of amplitude behavior fail. Further, ordinary (classical) flat layer refraction theory is too restricted to be very useful since our work requires a consideration of curvature effects and, more important, accurate representation of the effects of moderate velocity gradients (both negative and positive) on both sides of the transition zones. Thus asymptotic wave-theoretical expressions have been obtained for both SH and P-SV waves from a point source critically or nearly critically refracted from a spherical boundary, below which both the density and velocity may vary as a function of radius. This work is now at a stage where it may be, and to some extent has been, applied to the prediction and interpretation of source spectra.

Theoretical work in modal representations of the wave field was continued in the direction of surface wave and free oscillation mode excitation from representations of explosive and earthquake sources. In particular, the theory for surface waves in multilayered media generated by point forces has been generalized to include the multipole expansion for finite rupture surfaces and velocities in prestressed media. The surface wave synthesis program has been modified to include the more realistic sources. Work has also been initiated on the inclusion of realistic, detailed source representations in existing free oscillation programs.

These modal representations are especially important in the prediction of long-period radiation from seismic sources and have been utilized in the detailed studies of source spectral properties.

A summary of our work and accomplishments in wave propagation theory is as follows:

(1) Development of time-domain representation of the wave field, which, for "short time intervals" or in the near source distance range, provides essentially exact time-domain seismograms for waves in multilayered media. This approach has been developed in parallel with applications to both structural and source problems related to discrimination of seismic sources.

(2) Development of frequency-domain representations of the asymptotic (at high frequencies) wave field, applicable at any distance range, for body phases of any type. The theory is well developed at the present time and has been utilized in structural studies and in a preliminary fashion for source studies. Additional work involving Green's function representations, in the asymptotic limit, has been initiated and is continuing.

(3) Generalization of existing surface wave and simple ray theory representations to incorporate a variety of more or less sophisticated source theories has provided us with the capability of predicting teleseismic radiation fields from general models of the seismic source in realistic earth models.

Abstracts of papers dealing with wave propagation theory are given in section VI, part B.

IV. Seismic Source Theory and Observational Studies

The principal area of investigation under this grant has been observational and theoretical source studies. These studies are, of course, complemented by our other work, but the focus of our attention has been to provide a fundamental understanding of seismic sources. From the results of this work, we have attempted to extract practical and meaningful criteria for the understanding and identification of different kinds of events.

Our effort has been divided between theoretical considerations of seismic source models and observational studies designed to test the theories against observations. To a limited extent we have also used various of the theoretical models to infer source related parameters such as stress or stress drop, rupture velocity, as well as fault or rupture orientation and dimension. As we have become more confident of particular predictive capabilities of our models, we have made use of these capabilities as a means of interpreting some of our observations.

Our approach and general results may be summarized as follows:

(1) Basic theoretical work has in the main been related to formulation of relaxation source theory for general geometries of the failure zone (e.g., "flat" rupture zones) and for more general conditions of material failure, the latter being expressed in terms of the rheological behavior of the material in the failure zone. Rather general Green's function formulations have been developed to describe both the energy balance and dynamical behavior, as expressed by momentum conservation, during failure. The theory has been developed to include cases in which the failure zone retains shear stress so that shear-stress relaxation is only partial, as well as for the case in which melting occurs resulting in complete shear-stress relaxation within the failure zone. In conjunction with work in basic wave propagation theory, surface waves and body waves from relaxation source models (as well as from dislocation models and explosion source models) can now be predicted in realistic earth models. Both frequency-domain and time-domain representations of the field are available. A rather complete theoretical treatment of stress relaxation radiation effects due to an explosive-generated shatter zone having first-order spherical symmetry was also completed.

(2) Observational work can be separated into two categories:

(a) Comparative studies of the predictions of source theory representations of natural events based on relaxation models,

dislocation models, or special modified dislocation models such as that proposed by Brune, have been undertaken using observational data from a variety of earthquake regions. Most of the predictions common to all models presently utilized have been verified, in particular a characteristic frequency for earthquake sources, which has been termed a peak frequency or a corner frequency, that is related in a simple manner to the source dimension and the rupture velocity. The question of the level of the long-period radiation is still, however, unresolved, but it appears that a few earthquakes with strongly peaked source spectra have been observed.

In addition to work with earthquakes, explosive source representations have been checked against observations. It appears, for example, that the Haskell empirical representation for the reduced displacement potential is in error in that it predicts a source spectrum which is too low at the high-frequency end of the spectrum and somewhat high at the long-period end. The stress relaxation theory for explosions in a prestressed medium, assuming a roughly spherical shatter zone, appears to provide a very good explanation for the anomalous radiation from explosions.

(b) Determinations of source properties, as implied by observations of the seismic field. In this case equivalent source information is obtained, and before any interpretation is applied to it, these data are independent of any source theory. In this case we, of course, simply remove effects of propagation in the earth and hence obtain an equivalent source spectrum over some band of frequency. In most cases, we have gone on to interpret the source spectrum in terms of one or more particular source theory. This serves to provide a check on the theories, inasmuch as we can compare the source parameters inferred in this manner against expected values. On the other hand, the equivalent source spectra obtained for explosions and earthquakes provide us with direct evidence, independent of source models, of the differences in the spectra of different classes of earthquakes, and between these earthquakes generally and explosions. We have cast some of this information into m_b versus M_s data which has been used to compare to predicted values for various source models and which has also been used to extend the empirical m_b- M_s relations for earthquakes and explosions.

Interpretations of the source spectra have been made using both relaxation models and dislocation models for the source, in particular with Brune's special dislocation model. The results obtained are quite reasonable on the basis of what is presently known, whichever model of the source is used. It appears in particular that only when the rupture velocity is low, is there any clear divergence between the theories in terms of the interpretation of the source spectrum as expressed by values of stress (or stress drop), rupture length, etc. However, in this case the Brune dislocation source is not strictly applicable since it implicitly assumes an infinite rupture velocity. Resolution

of the theoretical discrepancy at low frequencies is expected from the use of broad band and low frequency data which we are presently working on and from other data which should be available shortly. In any case, the values of stress and rupture length obtained in these applications are clearly of importance for an understanding of the earthquake process.

This summary is supplemented by the abstracts in section VI, part C, which describe the work in greater detail.

V. Instrument Installation/Data Acquisition Systems

We have continued our development of new instrumentation and have maintained and updated our previous instrumental capabilities. Our emphasis has been in the development and improvement of relatively long-period systems, for both permanent and portable installation. In addition we have designed data recording systems to be compatible with present and future demands of data processing.

Thus we have considered systems designs encompassing the instrumentation itself, the recording system, and the computer-oriented data processing and analysis. In this context, it is useful to view this whole complex as a single entity; we refer to it as an "automated data acquisition and processing system". In conjunction with the demands of other research, as well as the work under this grant, we have evolved the system illustrated diagramatically in Figure 1. Most of the equipment shown and the procedures indicated are presently existent. Figure 2 shows the details of the computer and automated detection system, this system is presently being set up in the form indicated. Figure 3 shows some details of the digital recording and event detection system.

Some of the personnel involved in the work connected with this system were supported under this grant and some of the equipment incorporated in the complete system was obtained under this contract.

The ultra-long-period stations at Lake Isabella, California, and Nana, Peru, operated well during this contract period with very little down time. Aging of the electronics is expected, however, to be a possible problem with continued operation and we hope to obtain support for replacements in the future. Good results were obtained from both stations from the February 9th San Fernando earthquake, and the strain observations were especially valuable. Experiments, using ultra-narrow-band filters in the long-period range, for the detection of very small distant events are still in progress.

The normal yearly maintenance and calibration work at Nana, Peru, was postponed due to lack of funds. The end tanks on the Mercury-pendulum seismometers were replaced in order to allow more precise calibration procedures to be used, in conformity with the Nana facility. When this was accomplished, a significant noise reduction was achieved. Further, the strain transducer assemblies at the Isabella station were hermetically sealed to provide moisture protection.

VII. ABSTRACTS OF PUBLICATIONS AND REPORTS DURING THIS CONTRACT PERIOD

A. EARTH STRUCTURE AND INVERSION THEORY

The Effect of Anelasticity on the Periods of the Earth's Free Oscillations

Array Analysis of P'P' and P'dP' Seismic Phases

P-Wave Travel Time Anomalies from the Aleutian Arc

The Composition and Evolution of Earth and Mars

Resolvable Features of a Family of Earth Models

Systematic Inversion of Continental Heat Flow and Temperature Data

Wave Propagation in the Crust and Upper Mantle

A Procedure and Formulation for Elucidating Fine Structure of the Crust and Upper Mantle from Seismological Data

Regional Variations in the Structure of the Crust and Upper Mantle in the Central United States. Part 1. Crustal Structure from P Wave Spectra

Regional Variations in the Structure of the Crust and Upper Mantle in the Central United States. Part 2. Upper Mantle Structure from P and S Wave Spectra

Numerical Seismograms of Long Period Body Waves from 10° to 40°

Long Period Body Wave Propagation from 4° to 13°

Thermal Models for the Earth

Crustal and Upper Mantle Structure of the Columbia Plateau from Long-Range Seismic-Refraction Measurements

Velocity Gradients in the Continental Crust from Head-Wave Amplitudes

An Application of a Stochastic Inverse to the Geophysical Inverse Problem

Reflections of P'P' Seismic Waves from 0 to 150 km Depth Under the Ninety East Ridge, Indian Ocean, and the Atlantic-Indian Rise

B. SEISMIC WAVE PROPAGATION THEORY

An Earth-Flattening Transformation for Waves from a Point Source

Asymptotic Body Wave Theory for a Spherical Earth with Radial Velocity Gradients

Potentials for Elastic Displacement in Spherically Symmetric Media

An Elasticity Theorem for Heterogeneous Media, with an Example of Body Wave Dispersion in the Earth

High-Frequency Wave Propagation in the Earth

C. SEISMIC SOURCE THEORY AND OBSERVATIONAL STUDIES

Recent Studies in the Gulf of California and Investigation of the Source Parameter of Earthquakes in Northern Baja California

The Use of Body Wave Spectra in the Determination of Seismic Source Parameters

Source Dimensions, Seismic Moment and Stress Drop from the Shear Wave Spectra of Local Earthquakes in the Southern California Region

A Representation of Seismic Sources in Terms of Spectral Parameters Inferred from Body Waves

Report on the Lytle Creek Aftershock Sequence

Seismic Source Descriptions of Underground Explosions and a Depth Discriminate

Focal Mechanism of the October 21, 1965 Southeastern Missouri Earthquake and Rayleigh Wave Attenuation in North America

Theoretical Radiation Patterns and Spectra from Relaxation Models of Earthquakes

A Comparative Study of the Elastic Radiation Fields from Earthquakes and Underground Explosions

Representation Theorems in Prestressed Elastic Media with Moving Boundaries

Theoretical and Observed Distance Corrections for Rayleigh Wave Magnitude

Strains and Tilts Associated with the San Fernando Earthquake

A. EARTH STRUCTURE AND INVERSION THEORY

The Effect of Anelasticity on the Periods of the Earth's Free Oscillations, by Hsi-ping Liu and Charles B. Archambeau

It is known that the anelastic properties of the earth characterized by a "Q" structure will affect the periods of free oscillation. We have generally considered the effect to be negligible compared to the perturbing effects due to ellipticity and lateral inhomogeneities, for example. Nevertheless, it is of some interest to investigate the precise magnitude of this effect for the observed free oscillation modes since it could provide us with another constraint in the determination of the Q structure of the earth. An application of perturbation theory provides us with a good estimate of the magnitude of the changes in the periods of an elastic model due to inclusion of anelastic effects. Calculations based on currently accepted elastic and anelastic models for the earth show that the shift in period due to anelasticity is at most .002 percent for the toroidal modes ${}_0T_2$ to ${}_0T_{99}$, the maxima occurring near ${}_0T_{15}$ and at ${}_0T_{99}$. This is certainly the extreme limit of accuracy with which we can hope to determine these periods. However, the frequency shift is scaled by $(1/Q)^2$, so that the effect can be within the accuracy of the observations for more extreme, yet acceptable, Q models.

Array Analysis of P'P' and P'dP' Seismic Phases, by James H. Whitcomb

P'P' and P'dP', reflections at depth d in the mantle, are studied using the LASA array in Montana. Apparent slowness, or $dt/d\Delta$, is determined using beam-forming at epicentral distances between 55° and 80°. Errors in $dt/d\Delta$ due to shallow structure under LASA are evaluated by comparing northeasterly arrivals with southwesterly arrivals. The differences are found to be within the estimated ability of LASA to resolve $dt/d\Delta$ by beam-forming. The P'630P' phase is consistently found to be the strongest reflection preceding P'P', and shows the same relative amplitude distribution among the GH, AB, and DF branches as the main P'P' phase. Spectral power comparisons of the P'630P' phase to the P'P' phase show no difference from periods of 1.5 to 2.5 seconds. Thus, if the transition region is gradational, the majority of the velocity increase at 630 km must occur in about 5 km or less.

P-Wave Travel Time Anomalies from the Aleutian Arc, by Wayne Thatcher

Ray tracing through plate models and observed travel times from the nuclear explosion LONGSHOT and from natural earthquakes in the Aleutian arc suggest that P-waves which traverse the Aleutian plate are early up to 2 - 2 1/2 seconds compared with waves which do not. All rays travelling in the down-dip direction perpendicular to the strike of the arc and recorded at epicentral distances from 60° to 95° are early by approximately the same amount. USCGS listings since 1961 show low seismic activity below 100 km and no earthquakes deeper than 280 km. Teleseismic travel time residuals for the deepest shocks are small and can largely be accounted for by local corrections at the receiving station. The effect of plate dip, thickness, and velocity contrast on teleseismic travel

time residuals is investigated by ray tracing through a planar high velocity plate dipping into a spherical layered earth, and a fit to the observed values for the Aleutian arc is provided. Theoretical residuals plotted on the focal sphere are compared with the observations in order to determine the near-source structure.

The Composition and Evolution of Earth and Mars, by Don L. Anderson and Thomas H. Jordan

Ultrasonic, shock wave, body wave, and free oscillation data can be combined with recent advances in free oscillation resolving power theory to obtain bounds on the composition of the various regions of the Earth. Of the infinite number of Earth models that satisfy all available data, only those which satisfy, in addition, some smoothness criteria are accepted. These criteria are assigned on the basis of high resolution seismic data, resolving power constraints, or on constraints imposed by theoretical and experimental equations of state. All gross Earth data can be satisfied by an Earth model which has an upper mantle density of 3.3 g/cm^3 and a density gradient in the lower mantle which is slightly less than Adams-Williamson. The lower mantle is enriched in FeO and, probably, SiO_2 relative to the upper mantle; this is consistent with the composition derived from a meteorite analog. A case is made for sulfur, rather than silicon, being the light alloying element in the core. The new radius and moment of inertia for Mars demand that it have a dense central core. If Fe and FeS are the main components of the core, it can be between 0.4 and 0.5 of the radius of Mars, and between 0.1 and 0.17 of its mass. The zero-pressure density of the Martian mantle is high, about 3.5 g/cm^3. A satisfactory model for Mars can be constructed by placing two-thirds of the Fe, FeS and Ni of ordinary chondrites in the core and retaining some of the Fe in the mantle to raise its density. This implies that the temperature in the interior of Mars is between the entectic and the liquidus, or less than about 1300°C. The zero-pressure density of Mars' core is then 5.9 g/cm^3 which is 10% less dense than the Earth's core. The absence of detectable dynamo action in the core can be attributed to its smaller size, higher resistivity due to high sulfur content, screening by the mantle, and/or lack of lunar precessional torques.

Resolvable Features of a Family of Earth Models, by Thomas H. Jordan, Bernard Minster, and Don L. Anderson

Inversion of gross Earth data using the method of Jordan and Franklin has yielded models for shear velocity and density structure in the Earth's interior which are consistent with presumptions concerning the behavior of material with increasing pressure. Features evident in these models include a low-density gradient in the lower mantle and a non-zero rigidity in the inner core. Features absent in these models include a density reversal in the upper mantle. We examine the consistency of these features among the members of a family of models parameterized by an equation of state and belonging to the ensemble of models which satisfy sufficiently well the inaccurate data set. The response operator of the linear system is computed for several data sets, and the coupling through the data between perturbations in density and shear velocity is investigated. When the data set includes shear wave travel times between $\Delta = 30°$ and

95°, as well as eigenperiod data, perturbations of density and shear velocity in the lower mantle are uncoupled.

Systematic Inversion of Continental Heat Flow and Temperature Data, by Bernard Minster and Charles B. Archambeau

A simple thermal model of the crust and upper mantle under the North American continent is obtained by systematically inverting heat flow and temperature data in the steady state linear approximation. The stable method proposed by Jordan and Franklin is used to modify a starting model, under specified constraints. We successively present our assumptions, the construction of a starting model, and its inversion; the assumptions are discussed a posteriori. The results are compared with existing models and with information obtained from different geophysical approaches.

Wave Propagation in the Crust and Upper Mantle, by Donald V. Helmberger

Numerical seismograms are computed for a compressional pulse in a layered model. The simpler models consist of a fluid layer over a fluid halfspace, a fluid layer over a solid halfspace, and a solid layer over a solid halfspace. Restricted portions of the theoretical response for a layered model approximating the earth are constructed. Synthetic seismograms are generated using the pressure pulse appropriate for NTS events and the LRSM short- and long-period instrument responses. A detailed comparison between synthetics and observations show the advantages of using long-period data in complicated regions. The interplay between the PL wave, the refracted wave along the lid and the arrival from the bottom of the low velocity zone is displayed. A structural model appropriate for southwestern United States is presented.

A Procedure and Formulation for Elucidating Fine Structure of Crust and Upper Mantle from Seismological Data, by Tuneto Kurita

A routine procedure for determining fine structure of crust and upper mantle around recording stations is proposed: a cyclic procedure composed of a combined study of body wave spectra, surface wave dispersions, and travel-times, and a comparison of observed seismogram and synthetic one which includes source, propagational, and instrumental effects.

Theoretical formulation is made to elucidate a layered structure from body wave spectra. A strong advantage concerning the basic assumption of this method, compared with the other method, is that a postulation of horizontal parallel layering can be limited to a very narrow range. A separate determination of the structure of crust and upper mantle is proposed which utilizes truncated transfer ratio. In formulating this two-step procedure, factors which affect truncated transfer ratio, such as finite time length of record, window, instrumental response, and source function, are all taken into account. The validity of this procedure is examined and established for teleseismic records from deep-focus shocks. This procedure makes it possible to elucidate detailed structure such as transitional layering and minute configuration of the low-velocity zone.

Regional Variations in the Structure of the Crust and Upper Mantle in the Central United States. Part 1. Crustal Structure from P Wave Spectra, by Tuneto Kurita

Crustal structure in the central United States has been inferred from amplitude ratio and phase difference of long-period P waves observed at four WWSSN stations, SHA, OXF, FLO, and MDS. The general features of the crustal structure are summarized as follows:

(a) The crust is primarily approximated by a stack of horizontal parallel layers around these stations except for the region around FLO where the structure is complicated and an apparent coupling of crust and upper mantle is observed. Transitional layering over several km may exist.

(b) The crustal thickness of about 33 km on the Gulf of Mexico (SHA) thickens to about 41 km around the intersection of the Gulf Coastal Plain and the Interior Plain (OXF), and to about 47 km or more in the midst of the Interior Plain (FLO), thinning to about 41 km around the intersection of the Interior Plain and the Shield to the north (MDS).

(c) 3.00 km/sec sedimentary layer is confined to the Gulf Coastal Plain, the thickness of which is 3 km on the Gulf of Mexico (SHA), tapering out to the Interior Plain.

(d) Existence of 5.00-5.40 km/sec surface or near-surface layer with 1 to 3 km thickness is a prevailing feature.

(e) 6.00-6.50 km/sec layer of about 14 km thickness of a silicic upper crust thickens to about 30 km around OXF, and to 36 km or more around FLO, thinning to about 29 km around MDS.

(f) Existence of 6.90-7.00 km/sec layer of about 10 km thickness of a mafic lower crust is a common feature except for the structure around FLO where more mafic 7.40 km/sec layer over 10 km thickness or more exists.

(g) Uppermost mantle velocity is about 8.10-8.15 km/sec, corresponding to an ultramafic material.

Regional Variations in the Structure of the Crust and Upper Mantle in the Central United States. Part 2. Upper Mantle Structure from P and S Wave Spectra, by Tuneto Kurita

Upper mantle structure down to 220 km in the central United States has been inferred from long-period P and S waves from deep-focus shocks observed at three WWSSN stations, SHA, OXF, and FLO. Complex spectral ratios of body waves, P_V (vertical)/P_H (horizontal), SV_V/SV_H, and SH/SV_H have been shown to be very useful for the detailed study of the upper mantle structure, especially for the determination of depth to the lower boundary of the low-velocity zone. Eclogitic density distribution has mostly failed to give good fit between observational and theoretical transfer ratios. When peridotitic density distribution is taken, the general features of the upper mantle structure of the best-fit models are described as follows:

(a) From the Interior Plain to the Gulf of Mexico, the low-velocity zone shifts to shallower depth with increasing its thickness and decreasing its velocity. This feature is unrelated to assumed density distribution, and minute configuration

of the low-velocity zone described below. The depth range of the low-velocity zone is located from 150 to 199 km under the Interior Plain (south of FLO), from 117 to 196 km under the Gulf Coastal Plain (south of OXF), and from 93 to 175 km under the continental shelf of the southern Gulf of Mexico (south of SHA). S wave velocity decrease at the upper boundary of the low-velocity zone is about 0.30, 0.40, and 0.70 km/sec under the corresponding regions, respectively. Probable error for the estimation of depth and velocity is about a few kilometers and 0.10 km/sec, respectively.

(b) The upper and lower boundaries of the low-velocity zone are sharp, the transition occurring over at most 10 km or so.

(c) Existence of the high-velocity horizon of 8.35 -8.50 km/sec in the lid zone is possible, but uncertain from the present analysis.

Numerical Seismograms of Long-Period Body Waves from 10° to 40°, by Donald V. Helmberger

Long-period wave propagation in the upper mantle is investigated by constructing synthetic seismograms for possible models. A model consisting of spherical layers is assumed. Generalized ray theory and the Cagniard-de Hoop method is used to obtain the transient response.

Most of the recent models predict a maximum in the P amplitude near 20°. Models containing prominent transition zones at 400 and 650 km have some waveform complexity in the ranges 23° to 29°. The situation is further complicated by the advent of the PP phase. The amplitude of the P phase at 30° is down to about 25 percent of its 20° maximum. The amplitude of the PP phase at 32° is comparable to P. Near 37° the PP phase grows rapidly reaching about twice the P phase amplitude near 40°. Models containing sharp transition zones produce high-frequency interferences at neighboring ranges. This phenomenon which is reoccurring at multiples of 20° is a likely explanation of the Pa phase. A few profiles of observations are presented for comparison.

Long-Period Body Wave Propagation from 4° to 13°, by Donald V. Helmberger

Numerical seismograms are computed for a compressional pulse in a layered model. The simpler models consist of a fluid layer over a fluid halfspace, a fluid layer over a solid halfspace, and a solid layer over a solid halfspace. Restricted portions of the theoretical response for a layered model approximating the earth are constructed. Synthetic seismograms are generated using the pressure pulse appropriate for NTS events and the long-period instrument response. The interplay between the PL wave, the refracted wave along the lid and the arrival from the base of the low velocity zone is displayed. A detailed comparison between the synthetics and observations indicates a prominent low velocity zone with appreciable seismic absorption. Observed regional waveshape characteristics are displayed and a reconnaissance map of lateral variations along the top of the mantle presented.

Thermal Models for the Earth, by Bernard Minster and Charles B. Archambeau

Thermal models of the crust and upper mantle under shields and ocean basins are obtained through a systematic inversion procedure using the stable inverse proposed by Jordan and Franklin. The steady-state approximation consistently requires either a high heat flow emerging from the lower mantle, or a highly radioactive crustal layer. It is shown, however, that more acceptable steady-state models can be obtained if we lower the surface heat flow by about .3 units.

The possibility of explaining this discrepancy by a slow transient effect is investigated, assuming that the superposition of a transient regime on a steady-state regime is a reasonable first approximation. We also show how global tectonics can provide a basis for the construction of such models.

Crustal and Upper Mantle Structure of the Columbia Plateau from Long-Range Seismic-Refraction Measurements, by David P. Hill

Seismic-refraction measurements were made along a 600 km profile extending due south from the Canadian border across the Columbia Plateau into eastern Oregon. The source for the seismic waves was a series of 20 high-energy chemical explosions detonated by the Canadian government in Greenbush Lake, British Columbia. First arrivals recorded along this profile are on the Pn travel-time branch. In northern Washington and central Oregon, their travel time is described by $T = \Delta/8.0 + 7.7$ sec, but in the Columbia Plateau the Pn arrivals are as much as 0.9 sec early with respect to this line. An interpretation of these Pn arrivals together with later crustal arrivals suggests that the crust under the Columbia Plateau is thinner by as much as 12 km or has an average P-wave velocity higher by as much as 0.8 km/sec than the 35-km-thick, 6.2 km/sec crust under the granitic-metamorphic terrain of northern Washington. A tentative interpretation of later arrivals recorded beyond 500 km from the shots suggests that a thin 8.4 km/sec horizon at a depth of 100 km may be present in the upper mantle beneath the Columbia Plateau and that this horizon may form the lid to a pronounced low-velocity zone extending to a depth of about 140 km.

Velocity Gradients in the Continental Crust from Head-Wave Amplitudes, by David P. Hill

Small velocity gradients in a refracting horizon have a pronounced effect on the spectral amplitudes of head waves. Negative velocity gradients and anelasticity (Q^{-1}) result in a similar amplitude decay with distance for narrow-bandwidth data. Positive velocity gradients result in a net amplitude gain with distance compared with the head wave from a homogeneous, perfectly elastic refractor. Wave-theoretical expressions for these effects applied to published amplitude data for the major crustal refraction branches P_g and P*, suggest that the "granitic" crust in the Basin and Range province has either negative velocity gradients of the order of 10^{-2} km/sec/km or an anelastic Q of the order of 400, whereas the "granitic" crust in the eastern United States and on the California coast has slightly positive velocity gradients. Similarly, the "basaltic" intermediate layer appears to have a negative gradient of the order of 10^{-2} sec^{-2} under the Snake River plain and null or slightly positive gradients under Lake Superior and Mississippi. Velocity gradients inferred from laboratory measurements on granite and basic igneous rocks, together with published geothermal

gradients are generally consistent with the gradients inferred from amplitude data.

An Application of a Stochastic Inverse to the Geophysical Inverse Problem, by Thomas H. Jordan and Bernard Minster

The inverse problem for gross Earth data can be reduced to an underdetermined linear system of integral equations of the first kind. Discussed in this paper is a theory for computing particular solutions to this linear system based on the stochastic inverse theory presented by Franklin. The stochastic inverse is derived and related to the generalized inverse of Penrose and Moore. A Backus-Gilbert type tradeoff curve is constructed for the problem of estimating the solution to the linear system in the presence of noise. It is shown that the stochastic inverse represents an optimal point on this tradeoff curve. In the appendix a useful form of the solution autocorrelation operator as a member of a one-parameter family of smoothing operators is derived.

Reflections of P'P' Seismic Waves from 0 to 150 km Depth Under the Ninety-East Ridge, Indian Ocean, and the Atlantic-Indian Rise, by James H. Whitcomb

P'dP' phases, that is, reflections of P'P' seismic waves at depth d, are investigated for $0 < d < 150$ km near the Ninety-East Ridge, Indian Ocean, and the Atlantic-Indian Rise, south of the Cape of Good Hope. The P'P' epicentral range is 55° to 80°.

Conversion of P'dP' travel times to depth values strongly depends on the times and relative amplitudes of the main P'P' branches, which until now have been uncertain. This conversion is made by comparing the observed travel time with the appropriate P'P' branch and computing the depth of reflection d from the time difference, using a reasonable velocity distribution. The P'P' data studied here best fit the times of Bolt's AB and DF branches and Adams and Randall's GH branch. The largest-amplitude branch is found to be GH between 55° and 62.5° epicentral distance, AB between 62.5° and 72°, and DF between 72° and 80°.

The largest amplitude of the P'P' phase reflecting in an ocean area can be a reflection from the ocean surface or ocean bottom, the latter being most common. The time separation between these two reflections can be up to 8 seconds for deep oceans. The beginning of the ocean-bottom reflection may be picked earlier if a slightly deeper reflector, such as the Moho, is present.

The data indicate that some of the earliest largest-amplitude P'P' arrivals delineate a discontinuity, possibly the Moho discontinuity, under part of the Ninety-East Ridge area. A depth for this discontinuity of 23 km is found under the ridge and beneath a shoal feature just to the west of the ridge. Errors in these depth estimates depend mostly on the velocity model used to reduce the data. Reflectors 2° north of the Atlantic-Indian Rise area are at 21 km, possibly shallowing towards the rise, and at 9 km.

A deeper reflecting zone is seen in the Ninety-East Ridge area at about 15°S latitude. Its lower bound is at 102 km 6.5° west of the ridge, deepens to 137 km 3.5° west of the ridge, and shallows to 87 km under the ridge both at 15°S and 7°S latitude. This feature is believed to be related to the tectonics that formed

the ridge itself. Magnetic and bathymetric evidence precludes the possibility that the Ninety-East Ridge is a crustal-spreading feature. Several possibilities could explain the depth variation of the reflecting zone. If the reflection zone is a partial-melting zone, the depth variation could be caused by migration of water or partial melt upward, leaving behind more solid rock and effectively shallowing the zone under the ridge. Or, thicker sediments at the sides of the ridge may act as a thermal blanket and raise temperatures underneath, thus lowering the melting zone to the west. If the base of the zone is the base of the lithosphere, the depth variation could be caused by compressive buckling of the lithosphere or by sinking of a lithospheric slab dipping west.

B. SEISMIC WAVE PROPAGATION THEORY

An Earth-Flattening Transformation for Waves from a Point Source, by David P. Hill

An earth-flattening transformation is developed for wave propagation problems that can be formulated in terms of uncoupled scalar Helmholtz equations. Through the transformation, wave problems in isotropic, spherically symmetric media with a specified radial heterogeneity can be expressed in terms of a flat geometry with a suitably modified vertical heterogeneity. The transformation is exact for homogeneous (no source) problems and is useful for normal mode studies. When a point source of waves is present, the earth-flattening transformation together with the Watson transform converts the reflected wave field from a sum over discrete, spherical eigenfunctions to an integral over continuous wave numbers in a flat geometry. The far-field form of this integral shares many properties with the Weyl integral and is useful for body-wave studies in a spherical earth.

Asymptotic Body Wave Theory for a Spherical Earth with Radial Velocity Gradients, by David P. Hill

Asymptotic wave-theoretical expressions have been obtained for waves from a point source critically or nearly critically refracted from a spherical boundary, below which both the velocity and density may vary as functions of radius. The effect of boundary curvature is found to map into an effective positive velocity gradient in the corresponding flat problem. For crustal and upper mantle body waves, the results can be summarized as follows: 1) In the special case of a critical negative velocity gradient (a gradient equal and opposite to the effective curvature gradient), the critically refracted wave reduces to the classical head wave for flat, homogeneous layers. 2) For gradients more negative than critical, the amplitude of the critically refracted wave decays more rapidly with distance than the classical head wave. 3) For positive, null, and gradients less negative than critical, the amplitude of the critically refracted wave decays less rapidly than the classical head wave, and at sufficiently large distances, the direct "diving" wave dominates the wave form. Preliminary indications from the application of these results to published Pn amplitude data suggest that the mantle lid has a negative velocity gradient in the western United States, and a null or slightly positive gradient in the eastern United States.

Potentials for Elastic Displacement in Spherically Symmetric Media, by Paul G. Richards

The choice of P and S designations is somewhat arbitrary in heterogeneous elastic media, but becomes precise in the high frequency limit of ray theory. This fact is used in a radially heterogeneous isotropic medium to establish three potentials (P, S, T) with the following properties: (i) every displacement solution is represented by some (P, S, T); (ii) $T(\underset{\sim}{r}, t)$ is decoupled from P and S, is a potential for SH motion, and satisfies a second-order wave equation; and (iii) the coupling of P and SV is represented by coupled equations in potentials P and S. At high frequencies these equations decouple (for an

important class of sources) into separate second-order wave equations for P and S. An important role, in this decoupled case, is played by the variable density. Several possibilities suggested by the general P and SV equations are also outlined.

An Elasticity Theorem for Heterogeneous Media, with an Example of Body Wave Dispersion in the Earth, by Paul G. Richards

An explicit surface integral expression is derived, for the divergence (div u) of elastic displacement in an inhomogeneous anisotropic medium. In isotropic media, simple ray theory methods permit approximate evaluation of the integral; and (to the same order) an approximate relation is found between div u and the irrotational component of u. The resulting formula for P-wave displacement is expected to find application in the study of seismic sources; it is used here to evaluate the frequency-dependent interference properties of P-waves, near the shadow boundary of the Earth's core.

High Frequency Wave Propagation in the Earth: Theory and Observation, by David P. Hill (Ph.D. Thesis)

The wave-theoretical analysis of acoustic and elastic waves refracted by a spherical boundary across which both velocity and density increase abruptly and thence either increase or decrease continuously with depth is formulated in terms of the general problem of waves generated at a steady point source and scattered by a radially heterogeneous spherical body. A displacement potential representation is used for the elastic problem that results in high frequency decoupling of P-SV motion in a spherically symmetric, radially heterogeneous medium. Through the application of an earth-flattening transformation on the radial solution and the Watson transform on the sum over eigenfunctions, the solution to the spherical problem for high frequencies is expressed as a Weyl integral for the corresponding half-space problem in which the effect of boundary curvature maps into an effective positive velocity gradient. The results of both analytical and numerical evaluation of this integral can be summarized as follows for body waves in the crust and upper mantle:

1) In the special case of a critical velocity gradient (a gradient equal and opposite to the effective curvature gradient), the critically refracted wave reduces to the classical head wave for flat, homogeneous layers.

2) For gradients more negative than critical, the amplitude of the critically refracted wave decays more rapidly with distance than the classical head wave.

3) For positive, null, and gradients less negative than critical, the amplitude of the critically refracted wave decays less rapidly with distance than the classical head wave, and at sufficiently large distances, the refracted wave can be adequately described in terms of ray-theoretical diving waves. At intermediate distances from the critical point, the spectral amplitude of the refracted wave is scalloped due to multiple diving wave interference.

These theoretical results applied to published amplitude data for P-waves refracted by the major crustal and upper mantle horizons (the Pg, P* and Pn travel-time branches) suggest that the "granitic" upper crust, the "basaltic"

lower crust, and the mantle lid all have negative or near-critical velocity gradients in the tectonically active western United States. On the other hand, the corresponding horizons in the stable eastern United States appear to have null or slightly positive velocity gradients. The distribution of negative and positive velocity gradients correlates closely with high heat flow in tectonic regions and normal heat flow in stable regions. The velocity gradients inferred from the amplitude data are generally consistent with those inferred from ultrasonic measurements of the effects of temperature and pressure on crustal and mantle rocks and probable geothermal gradients. A notable exception is the strong positive velocity gradient in the mantle lid beneath the eastern United States (2×10^{-3} sec^{-1}), which appears to require a compositional gradient to counter the effect of even a small geothermal gradient.

New seismic-refraction data were recorded along a 800 km profile extending due south from the Canadian border across the Columbia Plateau into eastern Oregon. The source for the seismic waves was a series of 20 high-energy chemical explosions detonated by the Canadian government in Greenbush Lake, British Columbia. The first arrivals recorded along this profile are on the Pn travel-time branch. In northern Washington and central Oregon their travel time is described by $T = \Delta/8.0 + 7.7$ sec, but in the Columbia Plateau the Pn arrivals are as much as 0.9 sec early with respect to this line. An interpretation of these Pn arrivals together with later crustal arrivals suggest that the crust under the Columbia Plateau is thinner by about 10 km and has a higher average P-wave velocity than the 35-km-thick, 62 km/sec crust under the granitic-metamorphic terrain of northern Washington. A tentative interpretation of later arrivals recorded beyond 500 km from the shots suggests that a thin 8.4 km/sec horizon may be present in the upper mantle beneath the Columbia Plateau and that this horizon may form the lid to a pronounced low-velocity zone extending to a depth of about 140 km.

C. SEISMIC SOURCE THEORY AND OBSERVATIONAL STUDIES

Recent Seismic Studies in the Gulf of California and Investigation of the Source Parameter of Earthquakes in Northern Baja California, by Wayne Thatcher

Seismic investigations in and around the northern Gulf of California have delineated crust-upper mantle structure there and brought to light some interesting contrasts in earthquake mechanism between sources in the Gulf itself and those in bordering northern Baja California.

From the dispersion of seismic surface waves it has been inferred that crustal thicknesses vary laterally from 10 to 20 km across the Gulf and are about 26 km in the Baja California peninsula. P-delay data in the Imperial Valley in southern California, 200 km north of the Gulf, suggest crustal thicknesses very similar to those found in the northern Gulf.

An unusually intense earthquake swarm which occurred in the northern Gulf of California during March 1969 has provided new information concerning the seismic processes which occur on an actively spreading oceanic ridge, and has placed some constraints on the elastic wave velocities beneath it. Comparison of these and other Gulf earthquakes with those in adjacent Baja California, 200 km to the west, reveals that Gulf sources have surface wave amplitudes one to two orders of magnitude greater than northern Baja California events with similar short-period body wave excitation. Measurements of the seismic shear wave spectra of the Baja sources have been interpreted in terms of rupture dimensions and seismic moment using the theory recently developed by Brune (1970). Source dimensions are generally smaller than those for earthquakes of similar body wave magnitude which occur in the Gulf and in southern California, and in some cases this difference is as much as an order of magnitude.

The Use of Body-Wave Spectra in the Determination of Seismic Source Parameters, by Thomas C. Hanks and Max Wyss

Teleseismic determinations of body-wave (P, S) spectra, interpreted in terms of the Brune (1970) seismic source model, are used to estimate the parameters seismic moment (M_o) and source dimension (r) for three large, shallow, strike-slip earthquakes occurring on nearly vertical fault planes and for which the same parameters can be determined from field (F) data. These earthquakes are (1) the Borrego Mountain, California, earthquake (April 9, 1968) for which ($\bar{M}_o(P) = 10.$, $\bar{M}_o(S) = 6.6$, and $M_o(F) = 3.6$) x 10^{25} dyne-cms and ($\bar{r}(P) = 13$, $\bar{r}(S) = 21$, and $L/2(F) = 17$) kms; (2) the Mudurnu Valley, Turkey, earthquake (July 22, 1967) for which ($\bar{M}_o(P) = 9.1$, $\bar{M}_o(S) = 8.5$, and $M_o(F) = 7.2$) x 10^{26} dyne-cms, and ($\bar{r}(P) = 38$, $\bar{r}(S) + 41$, and $L/2(F) = 40$) kms; and (3) the Dasht-e-Bayāz, Iran, earthquake (August 31, 1968) for which ($\bar{M}_o(P) = 4.8$, $\bar{M}_o(S) = 8.6$, and $M_o(F) = 18.$) x 10^{26} dyne-cms, and ($\bar{r}(p) = 47$, $\bar{r}(S) = 42$, and $L/2(F) = 40$) kms. The Brune (1970) model is well calibrated with respect to the determination of these parameters for the earthquakes considered. A minimum estimate for the radiated energy can be expressed in terms of M_o and r; this estimate is low by a factor of 3-10 with respect to the estimate obtained from energy-magnitude relations for these three earthquakes. The stress drops of these events are of the order of 10 bars.

Source Dimensions, Seismic Moment and Stress Drop from the Shear Wave Spectra of Local Earthquakes in the Southern California Region, by Wayne Thatcher and Thomas C. Hanks

S-wave spectra have been determined for over 40 local earthquakes ($2 < M_L < 5$) recorded on torsion seismographs operating at Pasadena and Santa Barbara at hypocentral distances of from 15 to 200 km. Three torsion instruments with differing free periods and static magnifications provide a useful range of recorded trace amplitudes and a total frequency bandwidth from 0.05 to 10 cps. The observations have been interpreted in terms of fault dimensions and seismic moment using the shear dislocation model of Brune. The rupture dimensions determined deviate considerably from a linear relationship between fault length and local magnitude, but the data are closer to the linear relationship proposed by Wyss and Brune (1968) than to Press's (1967) line. The seismic moments obtained from the S-spectra agree satisfactorily with those obtained by the AR method. Stress drops range from less than a bar to about 100 bars. In the Santa Barbara Channel, 13 events indicate that stress drop is an increasing function of M_L, but a similar relationship does not apply to the data for southern California as a whole. For these data fractional stress drop is not determined and remains a major uncertainty in estimating radiated energy and tectonic stress.

A Representation of Seismic Sources in Terms of Spectral Parameters Inferred from Body Waves, by Thomas C. Hanks and Wayne Thatcher

The seismic source parameters seismic moment (M_o), source dimension (r), stress drop ($\Delta\sigma$), effective stress (σ_{eff}), radiated energy (E_s), and apparent stress ($\eta\bar{\sigma}$) can all be expressed in terms of three spectral parameters which specify the Brune (1970) seismic source and which are measurable from observed body-wave spectra: Ω_o (the long-period spectral level), f_o (the corner frequency) and ϵ (the reciprocal of which measures the extent of f^{-1} spectral decay for $f > f_o$). All of the above source parameters can be easily extracted from a log-log plot of Ω_o versus f_o, (ϵ when < 1 entering as a parameter), but only three of them are independent. The apparent stress is proportional to the effective stress, not the average stress. The Ω_o-f_o diagram is especially convenient for comparisons within a chosen suite of seismic and/or explosive sources. The equation on which the Gutenberg-Richter energy (E_{GR})-magnitude (M_L) relation was originally based is cast into an approximate spectral form; E_{GR} can then be easily compared with E_s on the Ω_o-f_o diagram for an earthquake of any M_L. Within the framework of the (Ω_o, f_o, ϵ) relations, it is a simple matter to construct an earthquake magnitude scale directly related to the radiated energy (E_s).

Report on the Lytle Creek Aftershock Sequence, by Thomas C. Hanks, James N. Brune, Wayne Thatcher, and Brian Tucker

Approximately 100 events following the Lytle Creek, California earthquake (1430:53 GMT, 12 Sept. 1970, $M_L = 5.4$) have been recorded on high-gain, broad-band seismic systems operated by the California Institute of Technology and the University of California, San Diego, in a four-day interval beginning approximately six hours after the main shock. The sequence occurred on the San Jacinto fault in Cajon Pass, south and east of the bifurcation of the San Jacinto

and San Andreas faults. Aftershock locations have been determined from the seismograms of three portable stations located within 20 km of the epicenter and from the records at Cedar Springs ($\Delta \sim 10$ km) and Riverside ($\Delta \sim 30$ km). Preliminary results indicate that most of the aftershocks were confined to a volume whose dimension is less than 5 km. S-wave spectra of approximately 40 aftershocks have been determined and interpreted in terms of seismic source parameters. Fault length determinations for the aftershocks are typically less than 1 kilometer.

Seismic Source Descriptions of Underground Explosions and a Depth Discriminate, by Donald V. Helmberger and David G. Harkrider

Synthetic seismograms of both body waves and Rayleigh waves are used to determine the radiation field of a few large contained underground explosions. A number of possible source descriptions are investigated. The Haskell source function was found to be successful in comparing short-period observations with synthetics. A reduced displacement potential of the form, $\phi(t) = d_o t^{\xi} e^{-\eta t}$, fits the long- and short-period data. The source parameters appropriate for the Boxcar event are $\xi = .5$ and $\eta = .15$. Synthetic PL and Rayleigh waves are compared with observations from a number of different size events to determine the dependence of η on yield.

The amplitude of the long-period synthetic responses at ranges greater than about 12° increases rapidly as the source depth in increased. Thus the difference in spectral properties of explosions and earthquakes as discussed by Molnar and others can be partly explained by the depth effect. The theoretical ratio SP/LP, that is, the short-period divided by the long-period amplitude, is computed from 12° to 25° for the Johnson upper mantle model and the Boxcar source. A study of an earthquake which cannot be distinguished from an explosion using the M_B versus M_S criterion is investigated by the SP/LP discriminate.

Focal Mechanism of the October 21, 1965, Southeastern Missouri Earthquake and Rayleigh Wave Attenuation in North America, by Brian Mitchell

A focal mechanism solution for the southeastern Missouri earthquake of October 21, 1965, has been determined from the amplitude radiation patterns of fundamental- and first higher-mode Rayleigh waves. The period ranges over which these patterns were determined are 4-50 seconds for the fundamental mode and 4-10 seconds for the first higher mode. A fault plane striking N30°W, dipping 45°W, having a slip vector oriented 165° counter-clockwise from the northward horizontal along the fault plane, and located at a depth of 12 km is compatible with all of the observed patterns as well as with the first motions of compressional waves throughout North America.

A least-squares method for determining surface wave attenuation from a known earthquake source was developed and applied to the southeastern Missouri event. Preliminary results at a few periods yield attenuation values of 1250×10^{-6} km^{-1}, 185×10^{-6} km^{-1}, 124×10^{-6} km^{-1} at periods of 5, 20, and 30 seconds, respectively, for the fundamental Rayleigh mode, and 445×10^{-6} km^{-1} at a period of 6 seconds for the first higher Rayleigh mode.

Theoretical Radiation Patterns and Spectra from Relaxation Models of Earthquakes, by Charles B. Archambeau and Bernard Minster

A relaxation source model is used to compute the radiation field to be expected from an earthquake, wherein the phenomenon is described mathematically as an initial value problem. This approach utilizes a Green's function integral solution which is evaluated for the case in which a zone of failure is assumed to grow unilaterally in a prestressed medium. The geometry of this zone is taken to be ellipsoidal and the material in the failure zone is assumed to undergo at least temporary loss of rigidity so that the stress field in the medium surrounding the expanding transition zone must relax by a radiation process. We assume the geometry of the failure zone, namely, its physical dimensions as a function of time and the initial state of stress in the medium, as well as the rheological behavior of the material (e.g. vanishing of the shear modulus under failure and ideal elastic behavior outside the failure zone). Parameterizing these assumptions, we then predict the complete spectral and spatial characteristics of the radiation field from such a source and compare these predictions to observations from earthquakes. The theory, viewed in this manner, is consistent with the observations.

A Comparative Study of the Elastic Radiation Fields from Earthquakes and Underground Explosions, by D. G. Lambert and E. A. Flinn, and Charles B. Archambeau

A detailed analysis of the surface wave radiation from two underground explosions (the Bilby and Shoal events) and an earthquake (the Fallon event) with an epicenter at the site of one of the explosions indicates that: (1) The long-period radiation from the earthquake is closely matched by a pure quadrapole source, but at higher frequencies the radiation patterns show asymmetries indicating rupture propagation effects and requiring additional higher order multipole terms for the source equivalent; (2) The radiation from the explosions corresponds closely to a superposed monopole and pure quadrapole source equivalent with no indication of higher order multipole terms contributing within a frequency band comparable to that investigated for the earthquake. These results are interpreted in terms of a stress relaxation source theory. The behavior of the earthquake radiation field is found to be consistent with the predictions of the theory. The same theory is used to explain the anomalous quadrapole radiation from the explosion under the supposition that the quadrapole radiation arises from stress relaxation around a shock-generated fracture zone. In both cases the equivalent quadrapole is determined. A comparative analysis of the earthquake-explosion pair having common epicenters and points of observation illustrates the basic differences in the long-period radiation from these two kinds of sources. These results provide us with a basis for distinguishing between earthquakes and explosions as well as the means of estimating source parameters, such as stress, which are of fundamental geophysical interest.

Representation Theorems in Prestressed Elastic Media with Moving Boundaries, by Charles B. Archambeau and Bernard Minster

The representation of the elastic field in an unstressed medium with fixed boundaries has been formulated in terms of integral, or Green's function solutions by several authors. The results have been applied to yield a

representation of the field from seismic dislocation sources and for the solution of a variety of other problems. An extension of the representation theorems to prestressed media with both moving and fixed boundaries is straightforward, and has a clear application to the description of an earthquake. The nature of this extended integral representation is such that separate contributions arise from a volume integral over the body forces and a surface integral over the fixed and moving boundaries of the medium which are similar to the results for the fixed boundary representations. However, an additional term given by a volume integral over the entire prestressed region is present and corresponds to initial value contributions. This latter addition to the radiation field is due to the relaxation of the prestress field in response to changing boundary conditions within the medium. A simple analytical example is used to illustrate the nature of the radiation field to be expected from the relaxation effect, along with a general formulation of the entire integral solution.

Theoretical and Observed Distance Corrections for Rayleigh-Wave Magnitude, by R. W. Alewine, III

Critical examination of the distance correction factor used in the widely accepted formula for surface wave magnitude reveals that this empirically derived formula contains an energy absorption coefficient higher than that observed in typical continental structures, and thus should not be applied to events having purely continental travel paths. For epicentral distances less than 15°, this effect becomes especially severe. When the original Gutenberg theoretical surface wave magnitude formula with an appropriate continental energy dissipation coefficient is applied to explosion data from the Nevada Test Site, a consistent surface wave magnitude is obtained at all distances. Minor alterations to this formula are given on the basis of the amplitude-distance behavior due to dispersion of numerically calculated Rayleigh waves from a contained explosive source in a typical continental structure. A systematic method of normalizing Rayleigh-wave magnitudes obtained over different types of propagation paths is suggested. This normalization might provide a means for better separating natural events and explosions in the M_s/m_b plots.

Strains and Tilts Associated with the San Fernando Earthquake, by Pierre Jungels and Don L. Anderson

The San Fernando earthquake of February 9, 1971, was well recorded on the quartz seismometer and mercury tiltmeters at Caltech's Isabella station, 147 km north of the epicenter. Strains were recorded also on a laser strain meter at UCSD and 2 strain meters near the Nevada test site (respectively 210 and 380 km from the epicenter). The permanent offsets are consistent with the strain release that is inferred from the fault plane solution and surface breakage.

VII. PREVIOUS TECHNICAL REPORTS IN THIS SERIES

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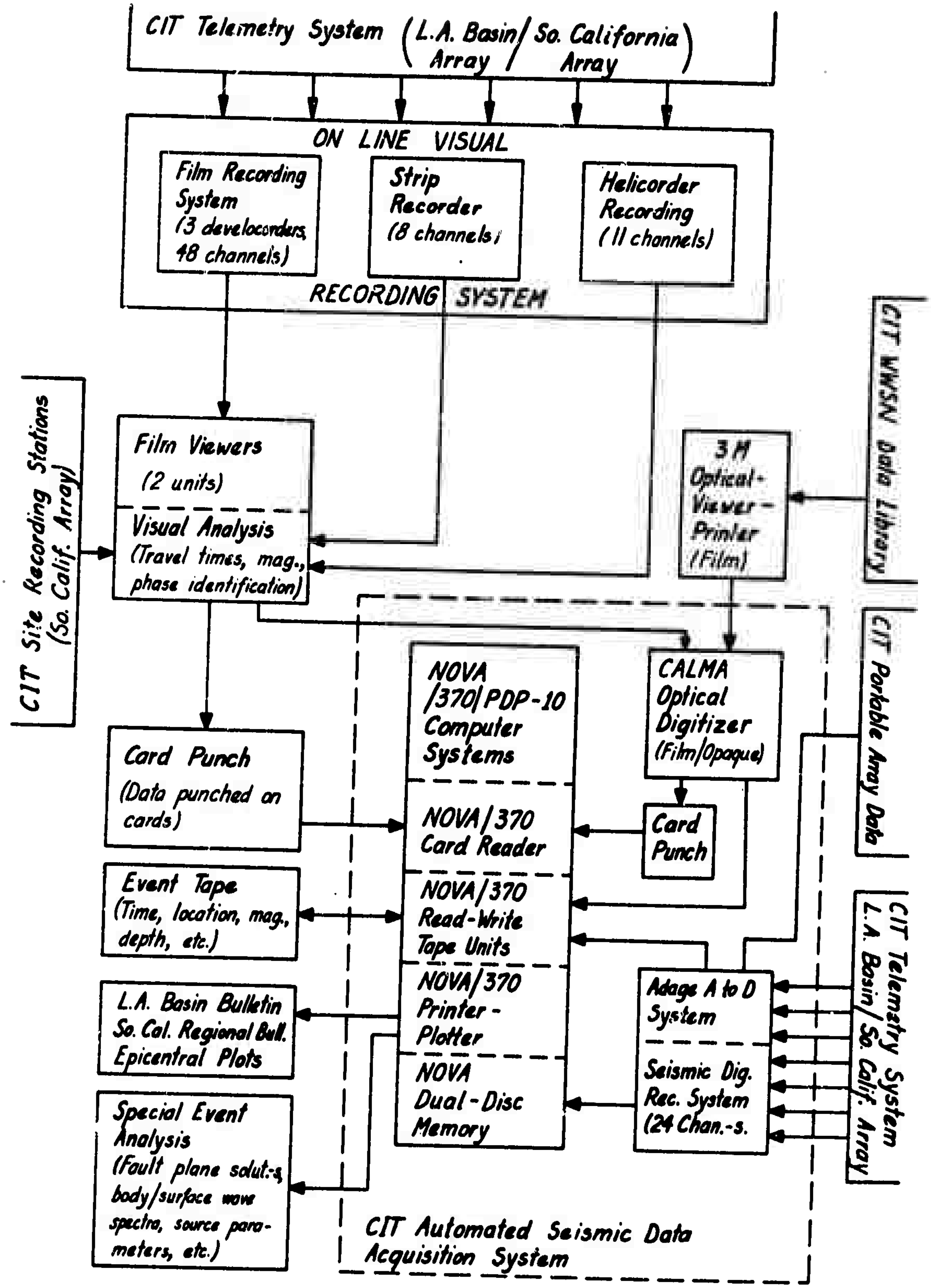

CIT Telemetry System (L.A. Basin Array / So. California Array)
ON LINE VISUAL RECORDING SYSTEM
Film Recording System (3 develocorders, 48 channels)
Strip Recorder (8 channels)
Helicorder Recording (11 channels)
CIT Site Recording Stations (So. Calif. Array)
Film Viewers (2 units)
Visual Analysis (Travel times, mag., phase identification)
CIT WWSN Data Library
3 M Optical-Viewer-Printer (Film)
CIT Portable Array Data
CALMA Optical Digitizer (Film/Opaque)
NOVA /370/PDP-10 Computer Systems
Card Punch (Data punched on cards)
NOVA/370 Card Reader
Card Punch
Event Tape (Time, location, mag., depth, etc.)
NOVA/370 Read-Write Tape Units
L.A. Basin Bulletin So. Cal. Regional Bull. Epicentral Plots
NOVA/370 Printer-Plotter
Adage A to D System
Seismic Dig. Rec. System (24 Chan.-s.
CIT Telemetry System L.A. Basin/So. Calif. Array
Special Event Analysis (Fault plane solut.-s, body/surface wave spectra, source parameters, etc.)
NOVA Dual-Disc Memory
CIT Automated Seismic Data Acquisition System

Fig. 1

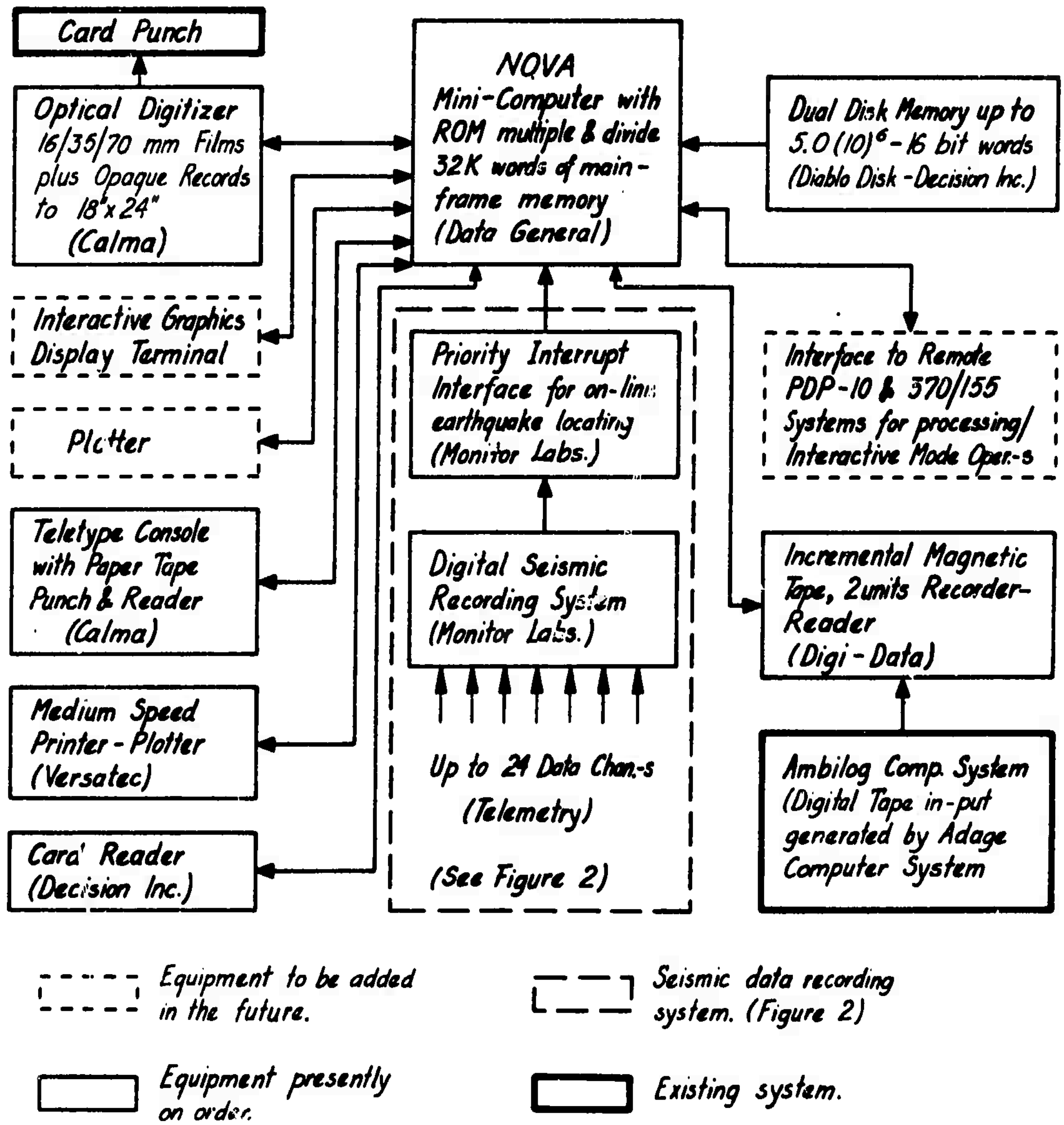
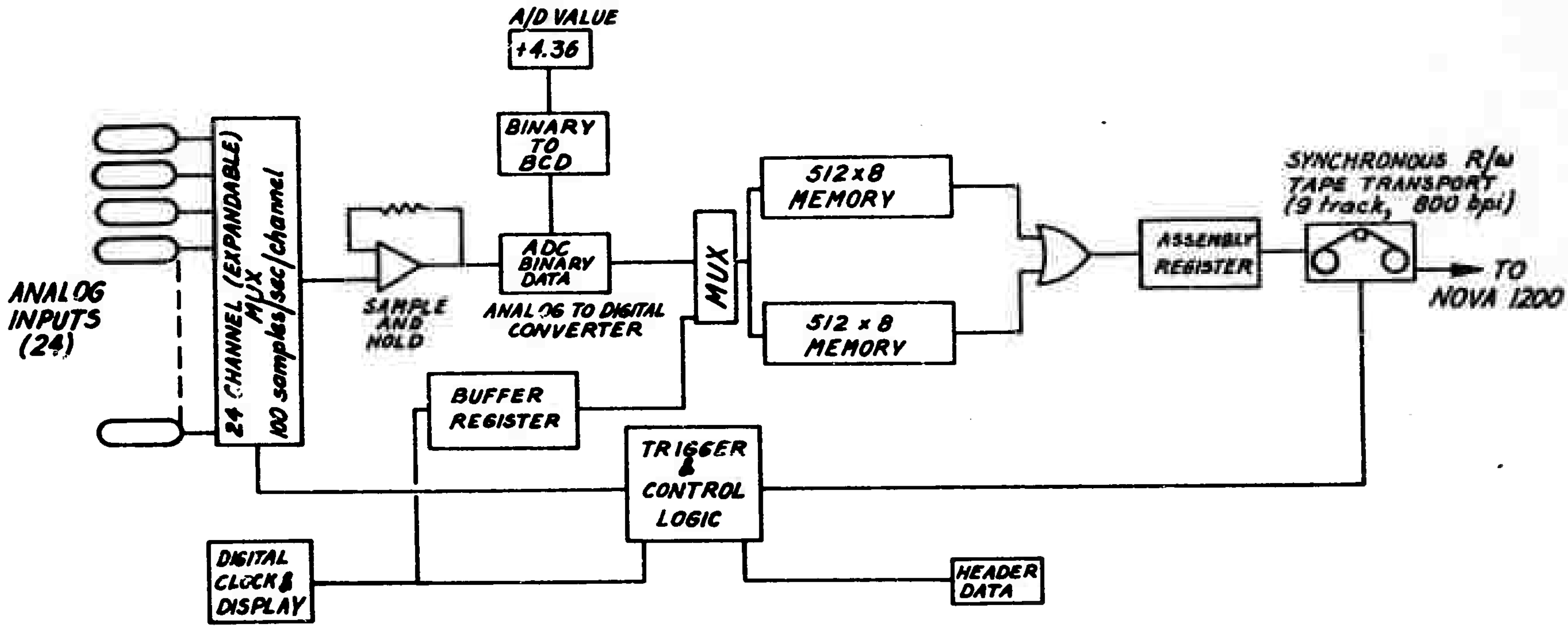


Fig. 2 CIT Automated Seismic Data Acquisition System.



CONTROL LOGIC - (Record Mode)

(a) Record digitally all channels if one channel exceeds selected threshold.

(b) Test all channels within a preset time interval (recognition time); if preset percentage of channels exceeds thresholds, then record all channels for a selected time interval (record time); otherwise back tape to last record overwritten with zeros.

(c) Priority Interrupt to NOVA, enter event tape seismograms on disk for processing.

Fig. 3